Shrinkage of Concrete with Replacement of Aggregate with Recycled Concrete Aggregate

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Synopsis: In this paper we present the experimental analysis of samples of concrete where portion of the natural aggregate were replaced with recycled aggregate originating from concrete (RCA). Experimental analysis to obtain the shrinkage properties (basic and dried) of the concrete containing recycled concrete aggregate (CRCA) was performed. The percentages of replacement of natural aggregate with RCA were 0%, 15%, 30%, 60% and 100% with test conditions of 50% RH and 20°C. The results of these trials are compared with reference concrete tests, at an age of 270 days. The results demonstrated an increase in the shrinkage of the CRCA that is proportional to the amount of RCA used as a replacement for the natural aggregate. When compared to the reference concrete, the drying shrinkage showing significant changes; however, their evolution over time is similar to standard concrete.

Key words: Basic shrinkage, recycled concrete, recycled concrete aggregate, shrinkage and shrinkage by drying.

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INTRODUCTION

It is known that the use of recycled concrete aggregate (RCA) in concrete involves an increase in the mortar content in the resulting concrete, and therefore, potential increases in shrinkage strain. Parallel to this, Kikuchi, Yasunaga and Ehara [1], together with Tavakoli and Soroushian [2], report the high importance of RCA quality with respect to the increase in strain due to shrinkage (ε_{sh}); or, stated in another way, the importance of the w/c ratio of the concrete which produced the RCA, its service history and period of hardening [3, 4], together with the process used in its production (a high level of refinement or elimination of the old mortar adhering to the natural aggregate translates into a reduction of shrinkage) [4]

In addition to the above, the purity of the employed RCA should be taken into account as a factor for the increase in shrinkage reported in the concrete containing recycled concrete aggregate (CRCA). The type and amount of contaminants that might be present in these aggregates have been reported by Yanagi, Nakagawa, Hisaka and Kasai [5] as another of the causes for the differences (they can generate increases of 129% to 150%) in the shrinkage behavior of the CRCA. In other papers on CRCA [6, 7, 8, 9, 10], the authors also discuss the shrinkage increases, which are usually found and establish typical ranges of increases, between 10% and 25% more compared to reference concretes. When all of the natural aggregates (both coarse and fine fractions) are replaced by RCA, increases in shrinkage may even reach 100%. Other research, also involving CRCA [1, 11, 12, 13, 14], has shown that the increase in coarse aggregate replacement correlates with the increase in shrinkage; this increase appears to be more plausible when the RCA exceeds a threshold percentage of the total aggregate content ($\geq$ 30%) [13, 14, 15]

In addition to these relationships, as with ordinary concretes, the CRCA also presents the correlations known in all concretes; an example of this is that existing between the w/c ratio of the concrete and the shrinkage increase [2, 4]

Finally, with respect to drying shrinkage ($\varepsilon_{sh\ dry}$) of CRCA only, the papers published up to now may be summarized as follows:

1. The increase in drying shrinkage of CRCA is imputable to the old mortar adhering to the natural aggregate, and also due to the content, interconnection and distribution of pore size [16, 17, 18].

2. The values may range from 20% to 70% more than the reference concrete, and when 100% of the aggregate is replaced, this increase may exceed 70% [19, 20, 21, 22, 23, 24], even reaching values of up to 263% more [25]

3. Attenuation of the increases in drying shrinkage of CRCA may be feasible through suitable use of shrinkage-reduction agents [26]

The main purpose of this paper is to explain on and provide practical information concerning the properties of drying shrinkage of CRCA, for which confirmation is sought in the scientific basis of their behavior and thus, to provide a solution to current application requirements.

EXPERIMENTAL DETAILS

Original Concrete

In this study 4 m^3 of original concrete (OC) was used. The concrete was made in a mixer and was placed into wooden formwork frames measuring 0.40 x 0.20 x 0.10 m. Fifty cylinders measuring 0.15 m in diameter x 0.30 m in height and four cubes 0.10 m were also used to study the porosity and mechanical behavior of OC.

Twenty-four hours after casting, the specimens were removed from the formwork and placed in the curing regime for 150 days (see Table 1, where the specific characteristics of this concrete are given). The specimens were then passed once through a semi-fixed roller grinder with an inlet width of 0.45 m and a maximum outlet size of 0.025 m. Finally, the resulting material was classified into sizes: 0-5, 5-10, 10-20 and 20-25 mm. The 5-10 and 10-20 mm fractions were used as RCA in this work.

Recycled Aggregate and Natural Aggregate

The designation used by sizes was: for RCA, gravel 10-20 mm and fine gravel 5-10 mm; and for the natural aggregate (NA), gravel 12-20 mm and fine gravel 5-12 mm.

The criterion used for this fit was the compacted maximum density (which reduced the possible influences of different particle size). These were:

- For RCA the combination was 55% gravel and 45% fine gravel.
- For NA the combination was 70% gravel and 30% fine gravel.

Table 2 shows the properties of the aggregate used. The RCA used in this study can be considered as being within the RILEM recommendation for TYPE II RCA (absorption ≤ 10% and $D_s \geq 2000$ kg/m^3); for the Belgian recommendation they are GBSBII (absorption < 9% and $D_s > 2100$ kg/m^3); and in the Japanese case they comply with the absorption requirement (absorption ≤ 7% and $D_s \geq$ 2200 kg/m^3) in the fractions used [27, 28, 29, 30] Consequently, the RCA employed in this study may be used in both plain and reinforced concrete if its application and factors of behavior are taken into account.

Mixture of Recycled Concretes

Due to the difficulty in determining the real w/c because of the high variation of absorption in the RCA, it was decided to use basic ACI 211.1 and ACI 211.2 mixture concepts proportioning with the following criteria:

1. The substitution of RCA for NA was done using equal volume fractions with the following condition:

   $$r = {RCA_{coarse}} \big/ {(RCA_{coarse} + NA_{coarse})} \qquad (0.00 \leq r \leq 1.00)$$

   Where: r = percentage of NA replaced by RCA, by volume; RCA_{coarse} = 55% recycled gravel + 45% recycled fine gravel; NA_{coarse} = 70% natural gravel + 30% natural fine gravel.

   The aggregate replacement percentages of the five samples of CRCA were: r = 0.00, 0.15, 0.30, 0.60 and 1.00. The fine aggregate used was, 100% crushed natural limestone sand from the Garraf quarry, Barcelona.

2. The RCA showed an increase in absorption proportional to the time spent in water. An immersion time of 20 minutes was used for the concrete mixtures, with up to 97% fine gravel and 77% gravel, and compared with the 24 hour absorption in all cases.

3. The amount of water absorbed by the aggregate was taken into account separately, in addition to its surface moisture before mixing and the free

water formed part of the mixture water. The above aspect is justified in criteria that were emphasized in previous publications of the authors [13, 14, 18, 31, 32, 33]

With the established mixing time and the required amount of water, the order of mixing the materials guaranteed (as far as possible) the immobility of the water and an improvement in the transition zone. The following sequence was adopted: (a) all of the coarse aggregate and water was introduced in the mixer; (b) these were mixed for 2 minutes; (c) the mixer was switched off for 3 minutes; (d) stages b and c were repeated twice; (e) the cement was introduced and mixed for 3 minutes; and (f) the sand was added and mixed for another 3 minutes.

The mixtures obtained using the above criteria are given in Table 3. The variation in consistency and volumetric proportions for the different percentages of aggregate replaced are within tolerable limits (slump 0.1 ± 0.03 m and concrete with volumetric proportion normal)

Properties of the Concretes

Tests were conducted on the different concretes included in the study to determine physical properties such as absorption, density, and porosity; and mechanical properties such as compressive and tensile strength, and Young's modulus. Table 4 shows the results of the tests, in which the Spanish Norm were used. For additional details on similar work, see previous publications by the authors [13, 14, 18, 31, 32, 33]

Shrinkage of the Concretes Containing RCA

Shrinkage tests were conducted on four cylinders measuring 0.15 m in diameter x 0.45 m in height for each of the proposed variables (28 in total). The strain measurements were made with embedded MM series EGP-type gauges fitted in the center of the concrete specimens. The specimens were kept in a curing chamber for 28 days (T = 20°C ± 2 and RH = 90% ± 5), after which they were moved to a climate chamber (T = 20°C and RH = 50%) until the end of the test period (270 days). The initial deformation measurements (t_0) were made 24 hours after the specimens had set. When the specimens were moved to the climate chamber, the surfaces of two of the samples for each variable under study (for basic shrinkage) were sealed with paraffin (3-mm-thick layer) and finally wrapped in three sheets of aluminium foil to prevent seepage of water from the chamber environment.

Figure 1 shows four samples during the preparation phase before commencing the drying process in the climatic chamber. From left to right, the first is a test specimen that is used to determine total shrinkage (un-coated surface) and the remaining three are test specimens used to determine basic shrinkage (the middle two were coated in paraffin, and the last was also wrapped in sheets of aluminum foil). Figure 2 show 12 of the 24 test specimens used in this experimental project during study in the climatic chamber.

Figures 3 and 4 show the behavior of the specimens during the initial curing chamber process and later climatic chamber drying. In all the figures, the curves represent the mean value for two test specimens, in which the expansion strains are expressed arbitrarily with a negative sign (-), whereas a positive sign (+) is used for shrinkage effects. It can be seen from these figures that the OC samples undergo greatest expansion (also known as swelling) during the curing chamber process. This is explained by the fact that, unlike the other CRCA samples, the OC samples undergo a prior period of ageing (150 days of curing conditions and 15 further days under laboratory conditions).

This ageing period, especially the 15 days of drying under laboratory conditions, leads to the loss of a large percentage of the water retained in the OC capillary pores, and when the test specimens are again placed in an environment with a high relative humidity, the expansion process is accelerated.

With respect to the CRCA samples, previous research work papers [13, 14, 34, 35, 36, 37, 38] have discussed the existence of certain differences concerning the expansion increase, together with the similarity in behavior with light or porous concretes. For our own study, we will say that the behavior of the CRCA samples shows an agreement between the replacement factor ***r*** and the expansion experienced during this first curing chamber phase, although it is important to note that there is also a notable separation of the CRCA curves into two well differentiated groups:

1) The curves for the variables ***r*** = 0.00, ***r*** = 0.15 and ***r*** = 0.30 are grouped together in the low or medium range (expansions in the order of -0.045 mm/m)

2) The curves for the variables ***r*** = 0.60 and ***r*** = 1.00 are grouped together in the range of maximum or high expansion (expansions in the order of -0.109 mm/m, which, in comparative terms, represents an increase of 2.5 times greater expansion).

After the time spent by the test specimens in the climatic chamber, there is a clear difference in behavior between those with free water loss (total shrinkage “$\varepsilon_{sh\ total}$”) and those which were sealed with paraffin wax and wrapped in aluminum foil (basic shrinkage “$\varepsilon_{sh\ basic}$”)

With regards to the basic shrinkage curves (Figure 3), it should be stated that the variables ***r*** = 0.60 and ***r*** = 1.00 rapidly recover part of the expansion undergone in the first stage and can even reach the other variables under study. The reference concrete is reached at approximately 4,500 hours (this recovery being approximately 50% of the strain caused by expansion), and finally, these variables demonstrate the greatest levels of expansion recovery (around 68% of the expansion undergone).

The remaining variables under study (***r*** = 0.00, ***r*** = 0.15 and ***r*** = 0.30) show slight recovery of the expansion strain at the beginning of the second period, after which they remain practically constant until the end of the study period (the expansion recovery of this set of variables only reached 22% of the expansion strain undergone).

For those test specimens showing total shrinkage during the climatic curing stage (Figure 4), it can be said that their behavior is notably similar for all samples at a young age; however, over time, the increase in the ***r*** factor reveals a behavior that is more proportional to the strain suffered by total shrinkage, which in turn is even more accentuated with time. The order of magnitudes of total shrinkage for CRCA is quite significant when compared with the reference concrete; with extreme values of: 0.561 mm/m for ***r*** = 1.00 compared to 0.394 mm/m for ***r*** = 0.00. These values of total shrinkage translate into an increase of 1.4 times more total shrinkage at an age of 270 days, these values being obtained from the accumulated behavior from the curing chamber stage.

With respect to the OC variable, referring to total shrinkage and for the climatic chamber stage, it can be said that its curve rises rapidly at the beginning, then continues to rise very steeply until it reaches a final total shrinkage value of only 0.065 mm/m. This can be explained by the fact that this concrete possesses a much greater level of maturity than the other samples studied, so that any possible increase in total shrinkage is predictably much less.

In order to obtain the real strain values for each of the properties in this study (only during the climatic chamber period), and thus make them useful for the design coefficient calculations, it was necessary to eliminate the values corresponding to the first stage of strain (curing chamber). In order to do this, the drying start time in the climatic chamber was set as zero (in other words t_0 = 28 days became t_0 = 0 days) and the corresponding strains were also set as zero, with the result that shrinkage (t_0 = 28 days) = 0 mm/m. Commencing with this standard, the other time and strain measurements were recalculated in relation to these points, and it was then a simple matter to obtain the real strain values for the climatic chamber stage.

Finally, effect superposition criteria were applied to each pair of total ($\varepsilon_{sh\ total}$) and basic ($\varepsilon_{sh\ basic}$) shrinkage values in order to obtain the real drying shrinkage values ($\varepsilon_{sh\ dry}$).

Figures 5 and 6 show the curves of basic shrinkage and total shrinkage after having carried out these modifications. In the first (Figure 5), it can be seen that the previously described grouping criterion continues to be applicable. On the one hand, the variables $\boldsymbol{r} = 0.60$ and $\boldsymbol{r} = 1.00$ can be located in the zone of maximum strain, whereas the variables $\boldsymbol{r} = 0.00$, $\boldsymbol{r} = 0.15$ and $\boldsymbol{r} = 0.30$ are located in the zone of low strain.

It is important to take note of the fact that these last three variables (in the same way as OC) still express the strain in the expansion zone; however, their values should be considered as being the product of the basic shrinkage phenomenon. This can be explained by the possibility that the hydration of the cement particles may be restricted not by lack of water, or by having exhausted the cement's hydration potential, but by the chemical bonds existing prior to this period in the climatic chamber. This results in a blocking of the space available for the cement particles to form new hydrated compounds. On the other hand, when dealing with concrete having a high content of recycled concrete aggregate (RCA), its high porosity and specific surface area, together with the possibility of contributing non-hydrated cement particles [13, 14, 18, 31, 32, 33], will allow the hydration to be prolonged for more time and thus achieve a better hydration process.

In quantitative terms, Table 5 contains the calculated values for the three types of strain ($\varepsilon_{sh\ basic}$, $\varepsilon_{sh\ total}$ and $\varepsilon_{sh\ dry}$) which were obtained from the climatic chamber stage. These values correspond to the usual age points that enable references or comparisons to be made with the mechanical properties previously above. In absolute values, the mean value of basic shrinkage for $\boldsymbol{r} = 1.00$ and $\boldsymbol{r} = 0.60$ is 0.050 mm/m, whereas for the group $\boldsymbol{r} = 0.30$, $\boldsymbol{r} = 0.15$ and $\boldsymbol{r} = 0.00$ this is only 0.007 mm/m at an age of 270 days; in other words, CRCA with high RCA content may reveal a value of basic shrinkage which is 7 times that of the reference concretes, with the disproportion being a direct function of concrete age.

With regards to total shrinkage (see Figure 6), the proportions calculated as a function of the reference concrete ($\boldsymbol{r} = 0.00$) are: 1.03 times more for $\boldsymbol{r} = 0.15$, 0.98 times for $\boldsymbol{r} = 0.30$, 1.25 times for $\boldsymbol{r} = 0.60$, 1.25 times for $\boldsymbol{r} = 1.00$, and 0.48 for OC at an age of 270 days. Finally, the reported drying shrinkage (see Figure 7 and Table 5) indicates that the shrinkage rate is high at early ages, and then slows down with time (after 180 days, for practical purposes the strain increase due to drying becomes a low constant rate). In addition to this, in the same way as the other properties mentioned above, replacement factors of RCA by natural aggregate above 30% ($r \geq 0.30$) cause a rapid increase in the values of drying shrinkage.

CONCLUSIONS

Based on the research and results presented in this paper, the following conclusions are reached:

Specific conclusions:

1. With regards to the expansion reported for the CRCA, we would say that this expansion is correlative with the factor ***r*** ; and that in addition, the ***r*** $\geq$ 0.60 factors show expansion increases, which are 2.5 times greater than the ***r*** $<$ 0.60 factors.

2. As far as the expansion recovery process is concerned, the factors contained in the range of ***r*** $\geq$ 0.60 require approximately 187 days to reach the other variables, ending in the recovery of an average of 68% of the expansion undergone at an age of 270 days, whereas the factors falling in the range of ***r*** $\leq$ 0.30 were only able to recover an average of 22% of the expansion undergone at the same age.

3. With respect to the basic shrinkage, the factors within the range ***r*** $\geq$ 0.60 show an average strain of 0.050 mm/m against an average of 0.007 mm/m for the factors in the range of ***r*** $\leq$ 0.30 (which is the equivalent of 7 times less).

4. For the property total shrinkage, the strain proportions seen as a function of the reference concrete are: ***r*** = 0.15 of 1.03 time more, 0.98 for ***r*** = 0.30, 1.25 for ***r*** = 0.60, 1.25 for ***r*** = 1.00, and 0.48 for OC at an age of 270 days.

5. Finally, the separation of the variables into two groups as stated above is also consistent with drying shrinkage; this threshold in the RCA content percentages leads to considerable CRCA strain increases.

General conclusions:

1. The use of RCA for the creation of CRCA is a viable, profitable technique provided that suitable conditions are employed in its implementation.

2. The shrinkage phenomenon is crucial in CRCA, given the characteristics and composition of the RCA, since these affect both the short and long-

term behavior of this type of concrete. This causes variations in their behavior coefficients and restricts their application if they are omitted or compared to conventional concretes.

3. The CRCA properties differ from those of ordinary concrete, including considerable increases in shrinkage. These increases correspond to the high porosity and permeability of the RCA, since they are only partly constituted (part old mortar and part natural aggregate).

4. The increase in the availability of water and hence the possibility of movement until water balance is attained with the surrounding environment cause both the drying shrinkage and its rate to increase in the CRCA.

5. In the case of basic shrinkage, the variations may be small in quantitative terms; however, there is a clear correlative increase with the factor $\boldsymbol{r}$.

6. It therefore appears that an RCA content which is less than 30% in the CRCA is both safe and feasible, provided that shrinkage inhibitors are not employed

ACKNOWLEDGEMENTS

The author would like to express their gratitude to the company Cervezas Finas de Cd. Serdán, S. A. de C. V., Puebla, México by the partial financing of this investigation; to the Technical University of Catalonia, Barcelona, Spain by the use of their facilities and to the Dr. L. Agulló and to the Dr. E. Vázquez.

REFERENCES

1. Kikuchi, M., A. Yasunaga and K. Ehara. (1993). “The total evaluation of recycled aggregate and recycle concrete”. Demolition and Reuse of Concrete and Masonry, Guidelines for Demolition and Reuse of Concrete and Masonry. Pp. 367–377, October. Edited by Lauritzen, E. K.

2. Tavakoli, M. and P. Soroushian. (1996). “Strengths of recycled aggregate concrete made using field-demolished concrete as aggregate”. ACI Materials Journal. Pp. 182–189, March – April.

3. Tazawa, E. and S. Miyazawa. (1993). “Autogenous shrinkage of concrete and its importance in concrete technology”. Creep and Shrinkage of

Concrete. Proceeding of the Fifth International RILEM Symposium. Edited by Bažant Z. P. and I. Carol. Pp. 159-168

4. Fujii, T. (1988). “Strength and drying shrinkage behavior of concrete using concrete crushed aggregate”. Demolition and Reuse of Concrete and Masonry, Vol. 2, Reuse of demolition waste. Pp. 660–669, November. Edited by Kasai, Y.

5. Yanagi, K., M. Nakagawa, M. Hisaka and Y. Kasai. (1988). “Effect of Impurities in recycled coarse aggregate upon a few properties of the concrete produced with it”. Demolition and Reuse of Concrete and Masonry, Vol. 2, Reuse of demolition waste. Pp. 613–622, November. Edited by Kasai, Y.

6. Sri Ravindrarajah, R. and C. T. Tam. (1988). “Methods of improving the quality of recycled aggregate concrete”. Demolition and Reuse of Concrete and Masonry, Vol. 2, Reuse of demolition waste. Pp. 575–584, November. Edited by Kasai, Y.

7. Hansen, T. C., and E. Bϕegh. (1995). “Elasticity and drying shrinkage of recycle–aggregate”. ACI Journal, No. 5. Pp. 648–652, September – October.

8. Nixon, P. J. (1979). “Recycled of the concrete”. Technology and Construction. Magazine of the Mexican Institute of the Cement and the Concrete, A. C. (IMCYC). Vol. 17. No. 102. Pp. 35-44, Mexico D. F., Mexico. October. (In Spanish)

9. Yanagi, K., M. Hisaka and Y. Kasai. (1993). “Physical properties of recycled concrete using recycled coarse aggregate made of concrete with finishing materials”. Demolition and Reuse of Concrete and Masonry, Guidelines for Demolition and Reuse of Concrete and Masonry. Pp. 379–390, October. Edited by Lauritzen, E. K.

10. Ujike, Isao. (2000). “Air and water permeability of concrete with recycled aggregate”. International workshop on recycled concrete. JSPS 76 Committee on Construction Materials. Pp. 95-106

11. Matsushita, H., H. Tsuruta and Takao Chikada. (2000). “Experimental studies on compressive strength and drying shrinkage of recycled aggregate concrete”. International seminar on recycled concrete. Sponsored by Niigata University and Japan Concrete Institute (JCI). Pp. 69-78

12. Hasaba, S., M. Kawamura, K. Toorii and K. Takemoto. (1981). “Drying shrinkage and durability of the concrete made of recycled concrete

aggregates”. Transactions of the Japan Concrete Institute. Vol. 3. Pp. 55–60

13. Gómez, José M., E. Vázquez y L. Agulló. (2001). “Strength and deformation properties of recycled aggregate concrete”. Fifth CANMET/ACI International Conference on Recent Advances in Concrete Technology. Supplementary Papers. Pp. 103-120. Singapore. August 2001. Compiled by Venturino, M.

14. Gómez, José M., L. Agulló y E. Vázquez. (2001). “Physical and mechanical properties of the recycled concrete aggregates. Application in concrete”. Technology and Construction. Magazine of the Mexican Institute of the Cement and the Concrete, A. C. (IMCYC). Vol. XIII, Num. 157, ISSN 0187-7895. Pp. 10-22, July 2001. Mexico D. F., Mexico. (In Spanish). http://www.imcyc.com/cyt/junio/cualidades.htm

15. Kashino, N. and Y. Takahashi. (1988). “Experimental studies of placement of recycled aggregate concrete”. Demolition and Reuse of Concrete and Masonry, Vol. 2, Reuse of demolition waste. Pp. 557–564, November. Edited by Kasai, Y.

16. Nishibayashi, S. and K. Yamura. (1988). “Mechanical properties and durability of concrete from recycled coarse aggregate prepared by chousing concrete”. Demolition and Reuse of Concrete and Masonry, Vol. 2, Reuse of demolition waste. Pp. 652–659, November. Edited by Kasai, Y.

17. Sakata, K. and T. Ayano. (2000). “Improvement of concrete with recycled aggregate”. CANMET/ACI. Durability of Concrete. Proceedings Fifth International Conference. Barcelona, Spain 2000 Edited by V. M. Malhotra Vol. II. Pp. 1089-1108.

18. Gómez, José M., L. Agulló y E. Vázquez. (2001). “Relationship between porosity and concrete properties with natural aggregate replacement by recycled concrete aggregate”. 2001 Second International Conference on Engineering Materials. ISBN 1-894662-00-8. Vol. 1. Pp. 147-156. August 2001. San José California, USA. Edited by Nagataki, S., A. Al-Manaseer and K. Sakata.

19. Environmental Council of Concrete Organizations. http://www.ecco.org

20. Hansen, T. C. (1992) “Recycled of Demolished Concrete and Masonry”. Report of Technical Committee 37-DRC Demolition and Reuse of Concrete. Part one. Pp. 1–160.

21. Bairagi, N. K., K. Ravande and V. K. Pareek. (1993). “Behavior of concrete with different proportions of natural and recycled aggregates”. Resources, Conservation and Recycling. Elsevier Science Publishers B.V. Vol. 9. Pp. 109 –126.

22. Vries, P. (1995). “Recycled materials for concrete. A report on the Dutch experience”. Journal Article. Quarry Mabagement. Vol. 22. No. 12. Pp. 23–26, December.

23. Ajdukiewicz, A. B. and A. T. Kliszczewicz. (1996). “Properties of structural concrete with rubble aggregate from demolition of RC/PC structures”. Concrete for Environment Enhancement and Protection. Pp. 73–80. Edited by Dhir, R. K. and T. D. Dyer.

24. Ravindrarajah, R., M. Stewart and d. Greco. (2000). “Variability of recycled concrete aggregate and its effects on concrete properties: A case study in Australia”. International workshop on recycled concrete. JSPS 76 Committee on Construction Materials. Pp. 9–25.

25. Henrichsen, A. (2001). “Creep and shrinkage in concrete with recycled aggregate –an attempt to review the present state – of – the – art”. Danish Recycled Cooperation. Dansk Beton Teknik A/S. (personal conference)

26. Yamato, T., M. Soeda and Y. Emoto. (2000). “Physical properties of recycled aggregate and the utilization as concrete aggregate. International Seminar on Recycled Concrete. Sponsored by Niigata University and Japan Concrete Institute (JCI). Pp. 59-68.

27. RILEM Recommendation. (1994). “121–DRG Guidance for demolition and reuse of concrete and masonry. Specifications for concrete with recycle aggregates”. Materials and Structures, No. 27. Pp. 557–559.

28. Hendriks, Ch. F. (1994). “Certification system for aggregates produced from building waste and demolished buildings”. Environmental Aspects of Construction with Waste Materials. Edited for Goumans, J. J. J. M., H. A. Van Der Sloot and T. G. Pp. 821–843.

29. Vyncke, J. and E. Rousseau. (1993). “Recycling of construction and waste in Belgium: actual situation and future evolution”. Demolition and Reuse of Concrete and Masonry, Guidelines for Demolition and Reuse of Concrete and Masonry. Edited for Lauritzen, E. K, October. Pp. 57–69.

30. Kasai, Y. (1993). “Guidelines and the present state of the reuse of demolished concrete in Japan”. Demolition and Reuse of Concrete

and Masonry, Guidelines for Demolition and Reuse of Concrete and Masonry. Edited for Lauritzen, E. K, October. Pp. 93–104.

31. Gómez, José M., E. Vázquez and L. Agulló. (2001). “Concrete with aggregate recycled. A guideline for the material”. Monograph M60-2001. ISBN: 84-89925-80-1. Pp. 1- 137. Barcelona, Spain. Edited by International Center of Numerical Methods in Engineering. (CIMNE). (In Spanish)

32. Gómez, José M., L. Agulló and E. Vázquez. (2001). “Repercussions on concrete permeability due to recycled concrete aggregate”. Third CANMET/ACI International Symposium on Sustainable Development of Cement and Concrete. ISBN 0-87031-041-0. SP 202-13. Pp. 181-195. September 2001. San Francisco, USA. Edited by V. M. Malhotra.

33. Gómez-Soberón, José M., E. Vázquez and L. Agulló. (2001). “Shrinkage and creep of recycled concrete interpreted by the porosity of their aggregate”. International Congress - Challenges of Concrete Construction. Dundee University. Scotland, RU. (Accept)

34. Mulheron, M. (1988). “The recycling of demolition debris: Current practice, products and standards in the United Kingdom“. Demolition and Reuse of Concrete and Masonry, Vol. 2, Reuse of demolition waste. Pp. 510–519, November. Edited by Kasai, Y.

35. López Javier. (1996). “The new Euro-code 2 Part 1-4: Concrete of aggregate light of closed texture”. Ready Concrete. No. 27. Pp. 38-42, September. (In Spanish)

36. Miyazawa, Shingo, T. Kuroi and R. Sato. (2000). “Fatigue behavior of reinforced concrete beam with recycled coarse aggregate”. International workshop on recycled concrete. JSPS 76 Committee on Construction Materials. Pp. 147-156

37. Sato, R., K. Kawai and Y. Baba. (2000). “Mechanical performance of reinforced recycled concrete beams”. International workshop on recycled concrete. JSPS 76 Committee on Construction Materials. Pp. 127-146

38. Yamato, T., Y. Emoto and M. Soeda. (1998). “Mechanical properties, drying shrinkage and thawing of concrete using recycled aggregate”. ACI Recent advances in concrete technology. Pp. 105–122.

List of Tables

List of Figures

Table 1 Mixtures used for original concrete.

Component	OC
Cement (kg/m^3) (*)	380
Water (kg/m^3)	168
Fine gravel (5-12) (kg/cm^3) (2*)	252
Gravel (12-20) (kg/cm^3) (2*)	773
Sand (0-5) (kg/m^3) (2*)	784
w/c	0.44
Coarse A / Fine A (Vol.)	1.3
Additives (Plasticizer) (l/m^3)	2.69

(*) CEM I 42.5 R (2*) Limestone aggregate, Garraf quarry, Barcelona

Table 2 Properties of recycled and natural aggregate.

Property	RCA			NA[*]		
	10-20	**5-10**	**0-5**[2*]	**12-20**	**5-12**	**0-5**
Dry specific gravity (kg/m^3)	2280	2260	2170	2570	2640	2570
Specific gravity (surface dry) (kg/m^3)	2410	2420	2350	2590	2670	2600
Water absorption (%)	5.828	6.806	8.160	0.876	1.134	1.49
Total porosity (%)	13.42	14.86	-----	2.70	2.82	-----
Shape index	0.363	0.466	-----	0.364	0.576	-----
Flakiness index	6	15	-----	8	19	-----
Modulus of fineness	7.2	6.2	3.8	6.9	5.0	3.3
Sand equivalent (%)	-----	-----	93.6	-----	-----	93.8
Particles < 200µ (%)	0.06	0.29	9.85	0.50	2.46	9.24

[*] Limestone aggregate, Garraf quarry, Barcelona [2*] not used to manufacture CRCA

Table 3 Mixtures used for recycled concrete.

Component		r = 1.00	r = 0.60	r = 0.30	r = 0.15	r = 0.00
Cement (kg/m^3)[*]		400				
Water (kg/m^3)		207.6				
RCA (kg/cm^3)	Fine gravel (5-10)	406	258	134	69	0
	Gravel (10-20)	497	315	164	84	0
NA (kg/cm^3)	Fine gravel (5-12) [2*]	0	268	488	604	710
	Gravel (12-20) [2*]	0	115	209	259	304
Sand (0-5) (kg/m^3) [2*]		662				
w/c		0.52				
Coarse A / Fine A (Vol.)		1.53				

[*] CEM I 52.5R UNE 80 301 96 RC/97 [2*] Limestone aggregate, Garraf quarry, Barcelona

Table 4 Mechanical and physical properties of recycled concrete.

	Tensile Strength (MPa)				Compressive Strength (MPa)				Young´s Modulus (GPa)				ABSORPTION (%)	WATER POROSITY (%)	D_s (kg/m^3)	D_{sss} (kg/m^3)
Age [*] / Factor	7	28	90	180	7	28	90	180	7	28	90	180				
r =0.00	3.6	3.7	3.9	4.1	33.3	39.0	42.1	47.0	27.6	29.7	32.4	32.9	8.40	18.0	2130	2310
r =0.15	3.3	3.7	3.9	4.1	33.9	38.1	41.6	46.6	27.2	291	30.1	30.8	8.60	18.5	2140	2360
r =0.30	3.3	3.6	3.9	4.0	34.8	37.0	39.5	44.1	26.5	27.8	29.4	29.9	8.60	18.5	2150	2330
r =0.60	3.2	3.4	3.7	3.9	30.6	35.8	38.3	44.1	25.5	26.6	27.6	27.0	9.00	19.2	2120	2320
r =1.00	3.5	3.3	3.6	3.9	30.7	34.5	37.5	43.0	26.9	26.7	26.4	26.5	9.60	20.1	2090	2290
OC	3.2	3.8	---	---	35.2	38.4	---	---	33.0	33.7	---	---	5.90	13.4	2270	2410
OC[2*]	4.1	4.1	4.2	4.3	45.1	45.4	47.0	48.4	35.2	34.5	34.6	34.9				

[*] Days [2*] 172, 193, 255 and 345 days of age

Table 5 Shrinkage of recycled concrete.

Strain (mm/m)	$\varepsilon_{sh\ basic}$	$\varepsilon_{sh\ total}$	$\varepsilon_{sh\ drying}$	$\varepsilon_{sh\ basic}$	$\varepsilon_{sh\ total}$	$\varepsilon_{sh\ drying}$	$\varepsilon_{sh\ basic}$	$\varepsilon_{sh\ total}$	$\varepsilon_{sh\ drying}$	$\varepsilon_{sh\ basic}$	$\varepsilon_{sh\ total}$	$\varepsilon_{sh\ drying}$
Age (*) / Factor	28			90			180			270		
r = 1.00	0.0010	0.2411	0.2401	0.0138	0.4166	0.4029	0.0280	0.5100	0.4820	0.0400	0.5280	0.4880
r = 0.60	-0.0283	0.2231	0.2514	0.0310	0.4414	0.4104	0.4338	0.5217	0.0879	0.0560	0.5370	0.4810
r = 0.30	-0.0017	0.2307	0.2324	-0.0040	0.3484	0.3524	-0.0060	0.4250	0.4310	-0.0030	0.4220	0.4250
r = 0.15	-0.0120	0.2367	0.2487	-0.0080	0.3683	0.3763	-0.0050	0.4268	0.4318	-0.0020	0.4410	0.4430
r = 0.00	-0.0190	0.2060	0.2250	-0.0220	0.3520	0.3740	-0.0210	0.4290	0.4500	-0.0160	0.4290	0.4450
OC (2*)	-0.0170	0.0771	0.0941	-0.0260	0.1680	0.1940	-0.0440	0.2020	0.2460	-0.0430	0.2041	0.2471

(*) Days (2*) Shrinkage (193, 255, 345 and 435 days)

Figure 1 Specimens preparation for trial.

Figure 2 Specimens in climatic chamber.

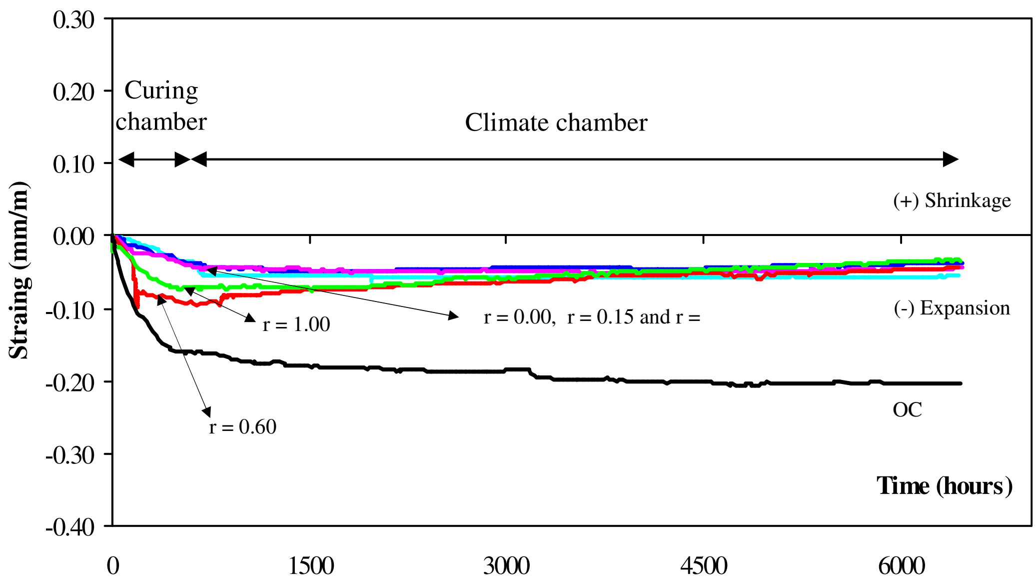

Figure 3 Deformation by swell and basic shrinkage for different recycled concrete.

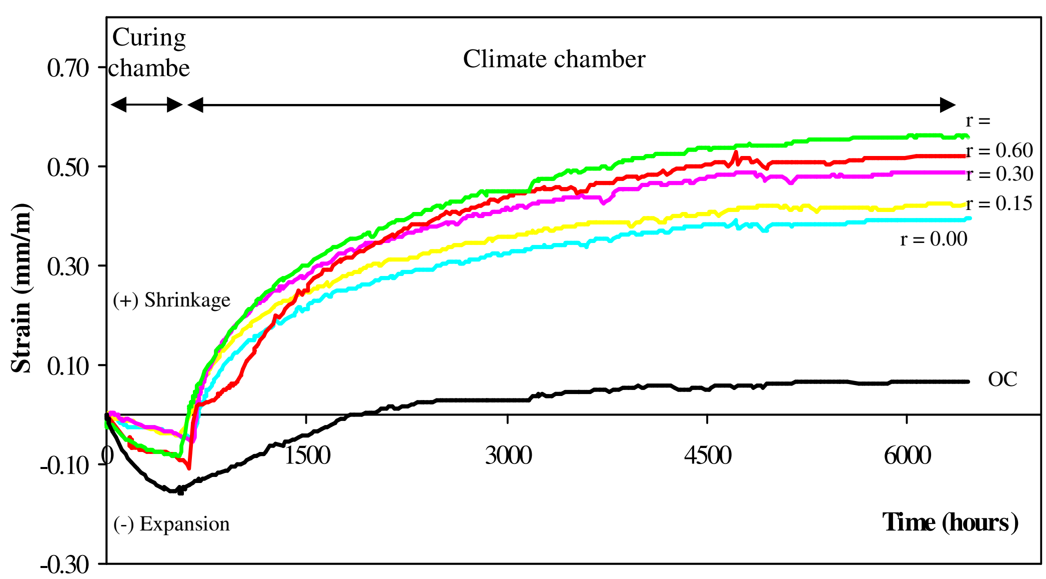

Figure 4 Deformation by swell and total shrinkage for different recycled concrete.

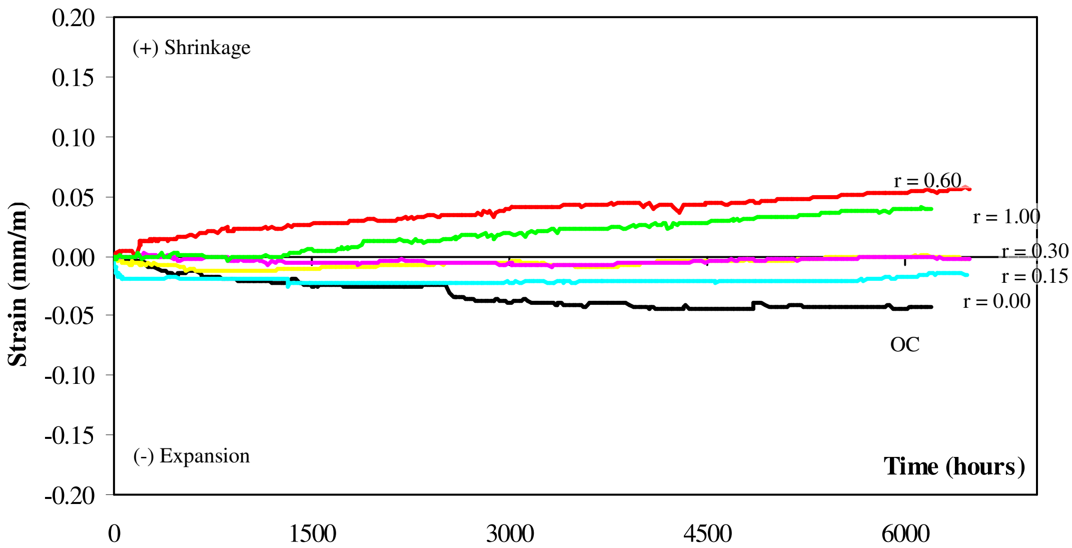

Figure 5 Basic shrinkage for different recycled concrete.

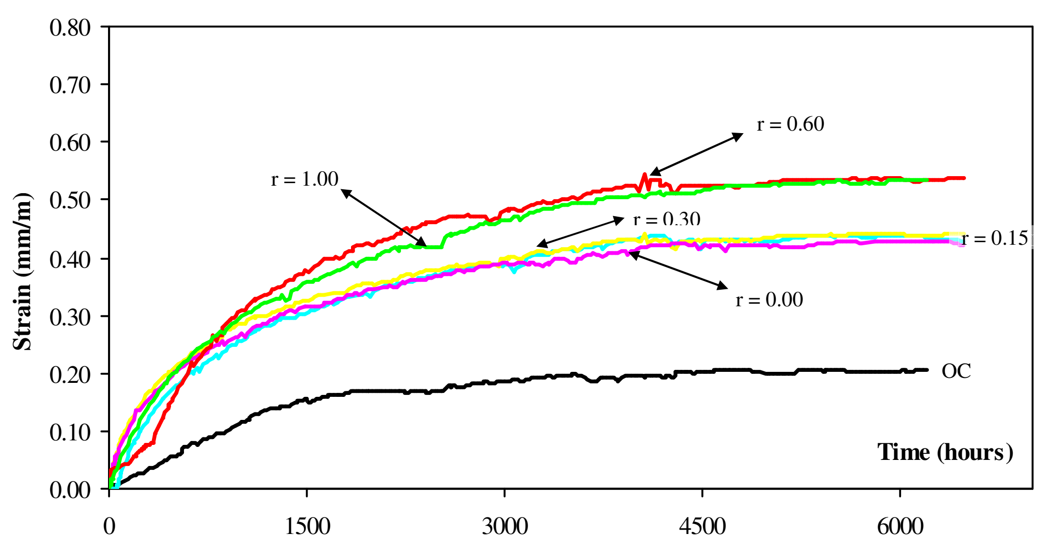

Figure 6 Total shrinkage for different recycled concrete.

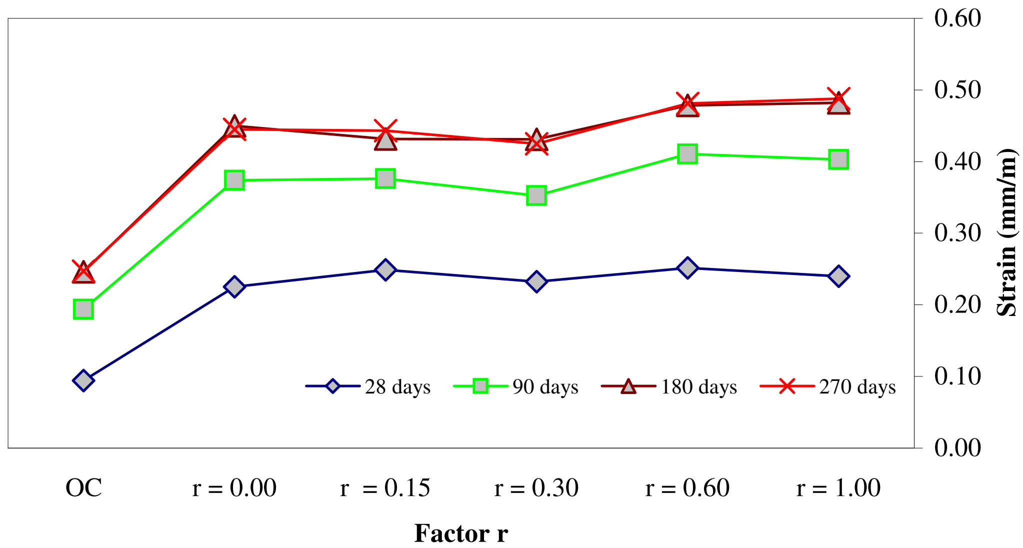

Figure 7 Shrinkage due to drying for different recycled concrete.